A COOL, DAMP PERIOD ASSOCIATED WITH THE SPRING-LIKE FRONTAL WAVES OVER THE EASTERN UNITED STATES, JULY 18-25, 1956

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1. INTRODUCTION

The occurrence of well-defined polar fronts in the Gulf Coast States during the month of July, while not necessarily a rarity, has been at least an unusual happening during the past several Julys. Upon reference to the Historical Weather Maps [1] it was noted that there have been Julys when as many as five polar fronts have swung southward over these Gulf States, while, on the other hand, there have been other Julys when the southern limit of the polar fronts has remained north of the 35th parallel. However, in most of the cases observed there was an ephemeral duration of the front in these southern latitudes; certainly few had the longevity of the case of July 18–25, 1956, the subject of the present study. That such prolonged activity should occur during a summertime frontal condition may in part have been due to the fact that temperatures in the airmass to the north of the front were considerably lower than the mean temperatures as shown by Showalter [2] in his study of summer airmass properties. And also that several stations in the southern portion of the country recorded temperatues in the upper air that were equal to or below the minimum values presented in the paper on "Extreme Temperatures in the Upper Air" [3].

Surface temperatures over the Eastern States during these situations can and often do vary greatly from year to year. This dependency it appears is closely related to the pressure distribution to the north of the front rather than to the frequency of frontal occurrence, or in other words to the resulting flow of air and the source region of the cool air. In the present study the persistency of the cold air (see fig. 1) was due to the formation and stagnation of a cold Low over the western Great Lakes region during the early portion of this period. Thus, while located in the Great Lakes region the Low could continue to reinforce the already cool air over the East by a constant flow of Canadian air from the Hudson Bay region, one of the principal source regions of cool air during the summer months in North America.

Precipitation associated with these fronts is frequently heavy in portions of the Gulf Coast and the Atlantic Coast States, and in this regard the July 1956 situation was no exception. However, the frequency of precipitation was even more outstanding with over 80 percent of the first-order weather stations in the eastern half of the country recording rain four or more days during this 8-day period (fig. 2). The area of greatest rainfall during this period occurred in the States of North Carolina, Virginia, and Maryland with the greater portion of the total having been obtained during a 12-hour period between July 19–20.

In this study it was decided to confine the discussion principally to the 0030 GMT surface maps and to the 0300 GMT upper air charts. This decision was occasioned by the length of the period covered, and because maximum instability and maximum temperatures would be most prevalent nearest those times.

2. ANTECEDENT CONDITIONS

A broad, flat, low pressure area, that eventually was associated with the genesis of the frontal system with which this article is concerned, first appeared in the region which extends northward from Colorado to the Province of Saskatchewan, Canada, as early as the morning of July 11, 1956. In the next 24 hours this broad trough moved eastward as it extended from a point just south of Lake Winnipeg, Canada into northern Mexico. Within the next 24 hours a 1007-mb. Low developed at the surface over central Wisconsin attended by frontogenesis. In the upper air, prior to the 13th, the 500-mb. chart presented a moderately deep Low centered over the eastern shore of Hudson Bay with a rather sharp trough that extended westward from James Bay to northern Lake Winnipeg. The maximum cyclonic vorticity associated with this upper trough was advected to the vicinity of the surface Low by the morning of the 13th to aid in the development and deepening of this new cyclonic center.

During the next 48 hours the central surface pressure lowered some 12 mb. as the Low moved northeastward through the St. Lawrence River Valley to the extreme eastern portion of Quebec Province. In this latter position it produced a northerly flow of air extending from the center of the Low to the axis of the High which was located along a line from the extreme western Great Lakes to the western portion of Hudson Bay. This northerly flow resulted in cold air pouring southward across most of

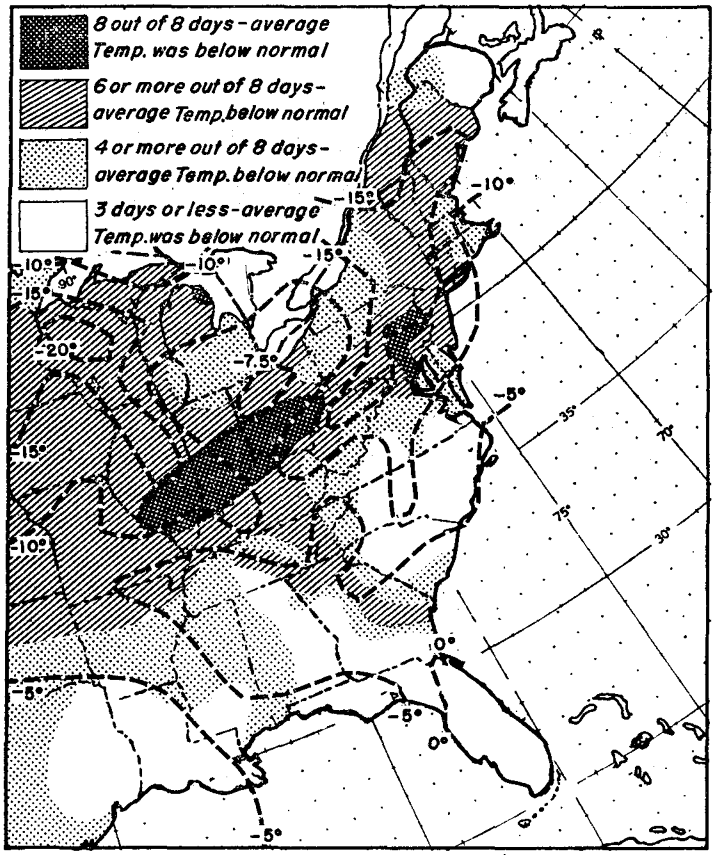

FIGURE 1.—Number of days during the 8-day period July 18–25, 1956 when daily average temperature was below the normal July value; total days of occurrence are indicated by different types of shading. Isolines show the largest one-day maximum temperature negative departure from normal July maximum. (Based on data from first-order stations.)

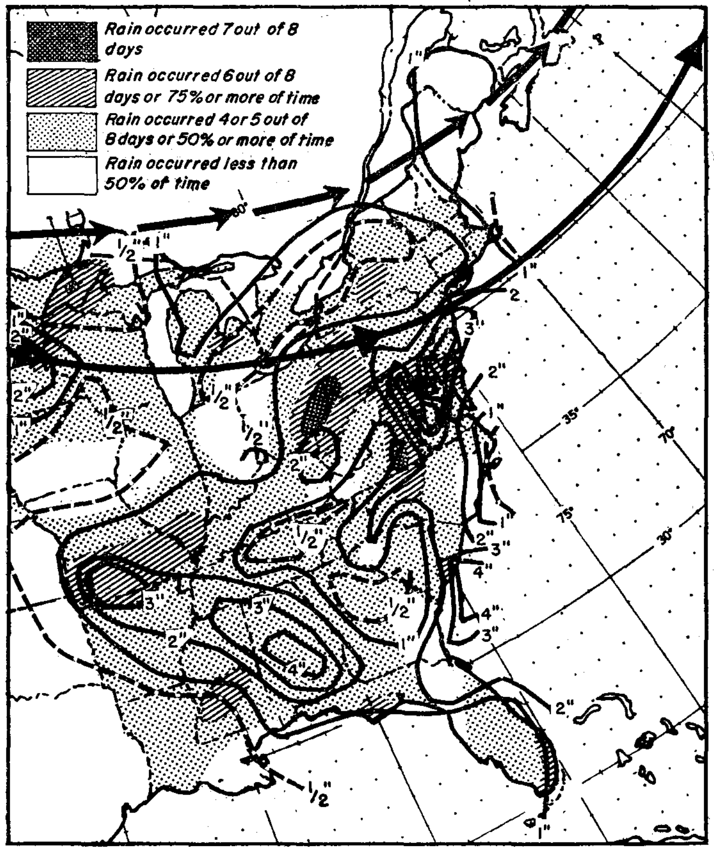

FIGURE 2.—Number of days during the 8-day period July 18–25, 1956 when a trace or more of precipitation occurred during a calendar day. Shading of different types has been used to distinguish different totals. Also shown are isohyets (continuous lines at one-inch intervals) for the period; isohyets in excess of 6 inches are omitted due to size of area. (Based on data from first-order stations.) Continuous, heavy, arrowed line shows average position of July 1956 700-mb. jet stream in comparison to normal July 700-mb. jet stream (broken, arrowed line).

northeastern United States and the intensification of the front as it stretched southwestward across the central Atlantic Coast States, the Ohio Valley, central Mississippi Valley, and into the Northern Plains.

In eastern Montana cyclogenesis was beginning to occur in conjunction with a 500-mb. trough over northern Alberta. Northwest of this new Low, pressures were rising at all levels in association with a building upper-level ridge.

By the morning of July 17, the surface trough extended southwesterly along the Atlantic Coast to the Virginia Capes, then westward to extreme southern Illinois where branching of this trough occurred; one arm extended northwestward to Lake Winnipeg, the other arm west-southwestward to central Oklahoma thence southwestward across central Texas. The surface front was in the main trough and followed the southern arm from the point of branching.

Associated with this surface picture was a broad upper-level trough over most of the area east of the Mississippi River. A major upper-level ridge was located along the west coast of the United States and Canada while a secondary ridge prevailed from western Texas to North Dakota. A small closed 500-mb. Low that had migrated from the northern portion of the Gulf of Alaska eastward along the 60th parallel started to curve sharply southward on the morning of July 17 and was centered near Reindeer Lake, Saskatchewan. The maximum cyclonic vorticity associated with this Low was to the north of Edmonton, Alta., in a favorable position to be advected over the surface trough near Lake Winnipeg, Sask. This presented a situation similar to that of the previously mentioned Low which had intensified rapidly over the Great Lakes region, except that in this present circumstance a strong band of westerlies prevailed across the west coast of the United States where previously a trough had existed.

3. SYNOPTIC SITUATION

In the early morning of July 18 (GMT) a cold front of moderate intensity was east of Sable Island, N. S., and extended in a southwesterly direction to near Wilmington, N. C., thence westward across the northern portion of the

Gulf Coast States, and terminated over north-central Texas (fig. 3A). Over the interior of the Nation the category of the front had been classified as weak on the basis of the gradient of the 1000–500-mb. thickness lines to the rear of the front. Because of widespread thunderstorm activity over the Southeastern States, the surface temperature discontinuity across the front was poorly defined in that area, but west of the Mississippi River surface temperature differences of from 12° to 20° F. were present.

The north-south orientation of the High near Lake Superior in conjunction with the Low over Labrador, Canada, insured a continued flow of cool Canadian air from the Hudson Bay region spreading over the Eastern States north of the surface front.

The 500-mb. constant pressure chart for 0300 GMT, July 18 (fig. 3B) presented a well-defined trough along the eastern seaboard of the United States with the attendant Low centered over Labrador, Canada. Another Low was centered in the vicinity of Lake Winnipeg, Canada, with its eastern periphery slightly west of Duluth, Minn. This latter Low, although weak, had cold-type characteristics and appeared to be nearly vertical to a minor surface depression. A pronounced belt of westerlies prevailed from the Northern Rockies to and beyond the coastline of Georgia, an unusually far southward displacement of the westerlies over the eastern portion of the country for the month of July.

The portion of the cold front which extended westward from the longitude of Bermuda and thence across the Southeastern States had practically ceased its southward progression by 0030 GMT of the 19th (fig. 3D). As the southward movement diminished, weak waves formed along the front. These waves initially had little significance and produced only minor amounts of precipitation. But there were indications that a wave formation near the junction of the States of Texas, Oklahoma, and Arkansas held considerable promise for future intensification. There, a developing flow of southerly winds in the lower levels of the atmosphere was advecting warm air northward from Mexico and the western Gulf of Mexico. However, the current dew point values were relatively low near the front at this time. High pressure, having increased both in area and intensity, stretched from Hudson Bay southeastward to off the New England coast. The surface center of the cold Low was located slightly west of St. Cloud, Minn., drifting east-southeastward. Precipitation over the eastern portion of the country during the past 24-hours had been quite light, but moderate to locally heavy shower activity was increasing in the trough area that extended from Arkansas northward.

At the 500-mb. level, the 0300 GMT chart on July 19 (fig. 3E) indicated a decreased flow of westerlies across the central Appalachians while the cold Low centered west of Duluth, Minn., had become a "cut-off" Low enclosed by the 18,800-ft. contour with an 18,700-ft. central height value. And the upper trough previously along the eastern seaboard was well off shore. Constant pressure heights over Florida had begun to rise after an easterly trough crossed the southern portion of the peninsula and moved into the Gulf of Mexico. An area of weak cyclonic vorticity had begun to develop over Oklahoma.

By the morning of the 20th the 0030 GMT surface chart (fig. 4A) indicated the apex of the wave over northwestern Alabama was enclosed by the 1014-mb. isobar. Other weak waves appeared to the east and west of this Low. The sea level pressure value of the cold Low, 1012 mb. indicated slight intensification and was located near Moline Ill., enclosed within a broad trough area that covered the Mississippi Valley region and wherein most of the precipitation had been confined during the past 24 hours. But it should be noted that considerable rainfall was beginning to occur ahead of the frontal waves outside of this trough area. High pressure continued to build and bridge across the front toward Bermuda. Concomitantly with the northward intensification of the Mississippi Valley trough and the building of the high pressure off the northeastern coast, the western periphery of the Bermuda High cell moved toward the southeast coast.

At the same time in the upper air the 500-mb. constant pressure chart (fig. 4B) indicated an expanding and increasing cyclonic flow about the cold Low centered southeast of Minneapolis, Minn. In fact, a zone of confluence was developing over Georgia and the Carolinas as the southerly flow over Florida increased from the westward building of the Bermuda anticyclone. With the establishment of the cold Low in the western Great Lakes region there was increased advection of cool outbreaks southward and eastward that produced short-wave troughs. This 500-mb. synoptic chart indicated a pronounced sharpening of the easternmost trough over eastern Georgia and eastern Tennessee, and a less pronounced trough extending from northwestern Missouri to eastern Oklahoma. The belt of westerlies had disappeared as the flow became more meridional due to the building of the ridges over western United States and off the east coast and to a Low centered over the North Central States. This developing southerly meridional flow over the Southeastern States was being intensified by a confluence zone in the area directly north of the sharpening trough. This increased northward advection of the thermal field (see thickness chart, fig. 4A) suggested further intensification of the off-shore ridge along with an increasing zone of maximum anticyclonic vorticity in the thermal field east of the Appalachian Mountains. The area of maximum cyclonic vorticity was in an excellent position to produce intensification of one of the waves.

During the subsequent 36-hour period from 0030 GMT of July 20 to 1230 GMT, July 21, exceedingly heavy rains occurred along a narrow strip extending from the vicinity of Savannah, Ga., northward into southeastern Pennsylvania then curving eastward into portions of extreme southern New England. Further discussion concerning this narrow region of heavy precipitation will be covered in other sections of this paper.

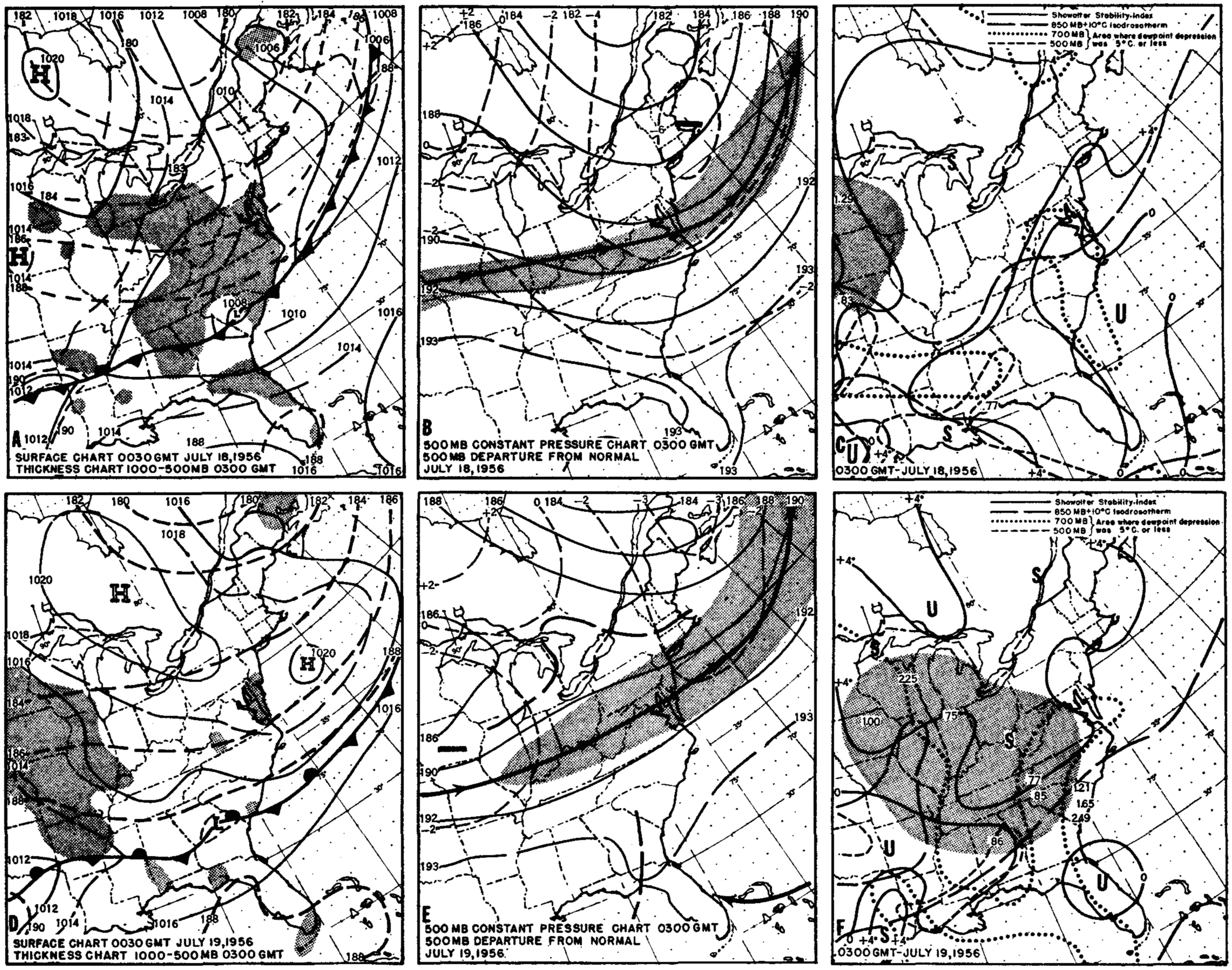

Figure 3.—(A) Sea level pressure pattern (solid lines) with fronts, 0030 GMT, and 1000–500-mb. thickness pattern (dashed lines) for 0300 GMT, July 18, 1956. Shading shows 24-hour precipitation area ending at 0630 GMT, July 18. (B) 500-mb. contour pattern (solid lines), 500-mb. departure from normal height (dashed lines), 200-mb. jet stream (heavy line with arrows indicating direction of movement), and winds of 75 knots or stronger (shaded area) all for 0300 GMT, July 18, 1956. (C) Composite chart of six semi-related items. 850-mb. dew point areas of +10° C. or higher (within long-dashed lines), 700-mb. areas with dew point depression 5° C. or less (within dotted lines), 500-mb. areas with dew point depression 5° C. or less (within short-dashed lines), calendar-day rainfall totals of 0.75 inch or more plotted at first-order stations, and Showalter stability index values (continuous lines at 4° C. intervals) with center of areas of stability and instability marked "S" and "U" respectively; all for 0300 GMT, July 18, 1956. Also shown is the area of vertical motion in excess of 0.005 m. p. s. (shaded) computed by the Joint Numerical Weather Prediction Unit for 1500 GMT, July 18. (D) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern at 0300 GMT, July 19, 1956. Shading shows 24-hour precipitation area ending at 0630 GMT, July 19. (E) 500-mb. contour pattern and departure from normal height, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 19, 1956. (F) Composite chart showing same elements as (C) for 0300 GMT, July 19, 1956. Vertical motion shown is for 1500 GMT, July 19.

Significant changes occurred during the next 24 hours in the pressure field distribution and the location of the front over the coastal States as illustrated by the surface chart for 0030 GMT, July 21 (fig. 4D). The rapid northward movement of the frontal system was concomitant with the intensification of the surface wave with apex near Washington, D. C. There was continued excellent frontal definition by the thickness pattern with strong negative relative vorticity in the thickness pattern about the apex of the wave, a condition considered favorable for the production of maximum rainfall occurrence (see Cressman [4]). It appears probable that this area of negative relative vorticity was advected nearly northward along the path of heaviest precipitation.

In the upper air at 0300 GMT, July 21 (fig. 4E) the rapid building and intensification of the eastern ridge was easily

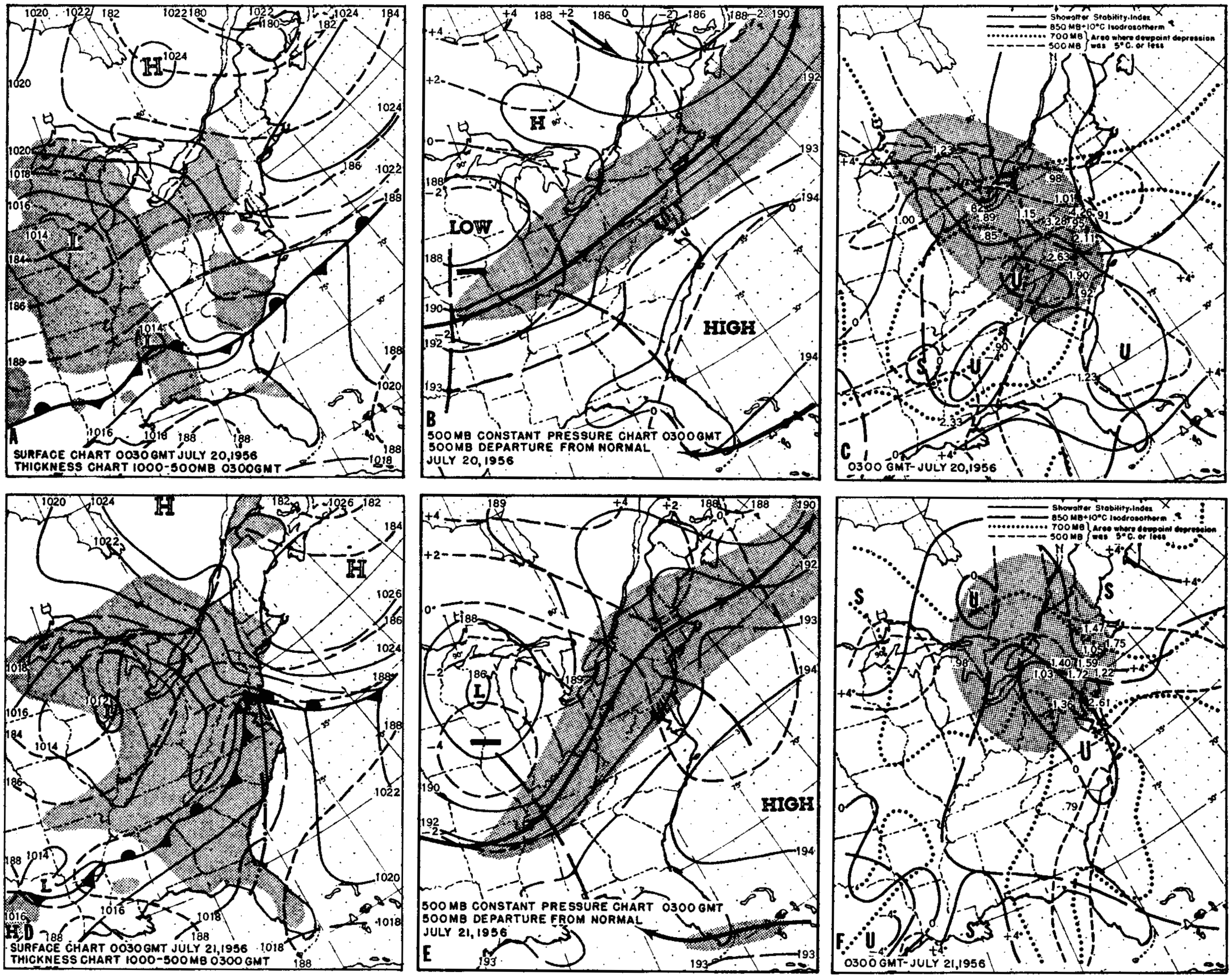

Figure 4.—(A) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern (dashed) for 0300 GMT, July 20, 1956. Shading shows 24-hour precipitation areas ending at 0630 GMT, July 20, 1956. (B) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 20, 1956. (C) Composite chart showing six semi-related items. 850-mb. dew point areas of +10° C. or higher, 700-mb. and 500-mb. areas with dew point depression 5° C. or less, calendar-day rainfall totals of 0.75 inch or more, and Showalter stability index values; all for 0300 GMT, July 20, 1956. Areas of positive vertical motion in excess of 0.005 m. p. s. (shaded) are for 1500 GMT, July 20. (D) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern for 0300 GMT, July 21, 1956. Shading shows 24-hour precipitation area ending at 0630 GMT, July 21. (E) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 21, 1956. (F) Composite chart showing same elements as (C) for 0300 GMT, July 21, 1956. Vertical motion areas for 1500 GMT, July 21.

apparent and with this building of high pressure, a definite block had been established that would hinder any immediate eastward displacement of the cold Low.

Generally over the remaining area of the Eastern States little significant change had occurred at either surface or aloft. Thus, there continued a more or less repetitious occurrence of weak short waves or cool outbreaks from the cold Low, waves along the front (mostly minor), and a slow eastward progression of the ridge area as the cold Low drifted northeastward. These conditions prevailed through the 0030 GMT surface chart and the 0300 GMT upper air charts of the 23d. Discussion concerning these charts has been omitted for the sake of brevity but the 24-hour sequence of charts is uninterrupted in figure 5 A, B, D, E. Precipitation continued to be rather widespread during this period with scattered totals of one or more inches.

On the morning of the 24th (GMT) (fig. 6A, B) the cold Low had again become approximately vertical and about stationary in the vicinity of Moosonee, Ont. Intensification of this Low had occurred at the surface and aloft with a definite trough indicated at upper levels from the

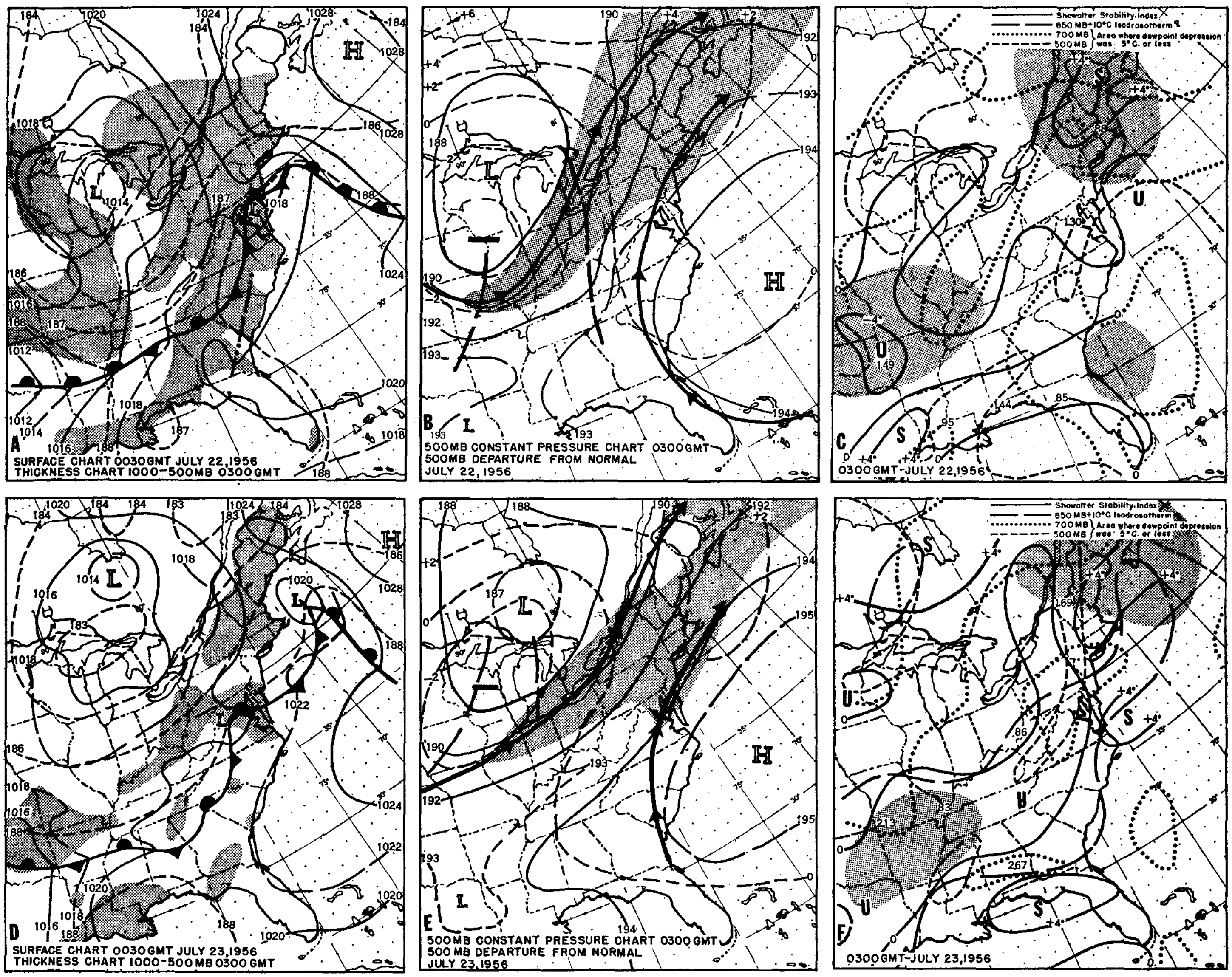

FIGURE 5.—(A) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern (dashed) for 0300 GMT, July 22, 1956. Shading shows 24-hour precipitation areas ending at 0630 GMT, July 22. (B) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 22, 1956. (C) Composite chart showing six semi-related items. 850-mb. areas of +10° C. or higher, 700-mb. and 500-mb. areas with dew point depression 5° C. or less, calendar-day rainfall totals of 0.75 inch or more, and Showalter stability index values; all for 0300 GMT, July 22, 1956. Areas of positive vertical motion in excess of 0.005 m. p. s. (shaded) are for 1500 GMT, July 22. (D) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern for 0300 GMT, July 23, 1956. Shading shows 24-hour precipitation area ending at 0630 GMT, July 23. (E) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 23, 1956. (F) Composite chart showing same elements as (C) for 0300 GMT, July 23, 1956. Vertical motion areas for 1500 GMT, July 23.

upper Great Lakes to northeastern Texas. Over the Atlantic there had been a gradual weakening and continued eastward drift at all levels of the anticyclone. To the rear of this High an occluded front and attendant Low, which previously was the pronounced wave near Washington, D. C., were headed toward Sable Island. In conjunction with these features was the return toward a more zonal flow over the Eastern States.

During the next 24-hour period (fig. 6D) there was pronounced weakening and partial dissipation of the frontal system over the eastern half of the nation in conjunction with decreasing thermal gradient. Concordant with this proceeding was the rapid invasion of another front over the upper Great Lakes region; the thermal pattern defining this front indicated that it had more of the characteristics of an occlusion or a trough of warm air aloft (TROWAL, as used by the Canadian Meteorological Service [5]) rather than a cold front. Pressure ahead of this front was falling as the High cell over the Atlantic Ocean continued to withdraw eastward. Precipitation persisted over a wide area to the north and west of the deteriorating front as a new zone of rainfall appeared in the upper Great Lakes.

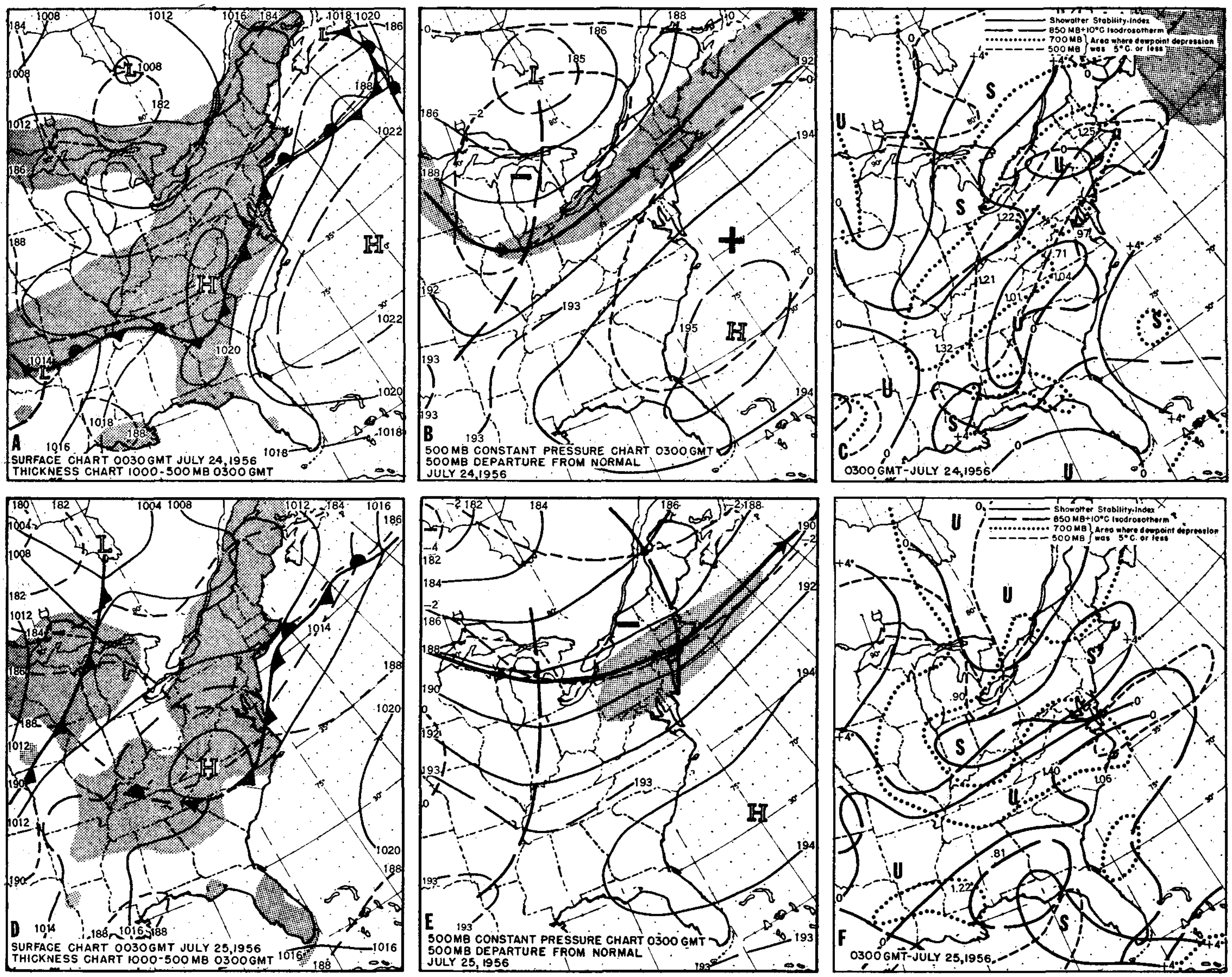

Figure 6.—(A) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern (dashed) for 0300 GMT, July 24, 1956. Shading shows 24-hour precipitation areas ending at 0630 GMT, July 24. (B) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 24, 1956. (C) Composite chart showing six semi-related items. 850-mb. dew point areas of +10° C. or higher, 700-mb. and 500-mb. areas with dew point depression 5° C. or less, calendar-day rainfall totals of 0.75 inch or more, and Showalter stability index values; all for 0300 GMT, July 24, 1956. (D) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern for 0300 GMT, July 25, 1956. Shading shows 24-hour precipitation area ending at 0630 GMT, July 25. (E) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 25, 1956. (F) Composite chart showing same elements as (C) for 0300 GMT, July 25, 1956. Vertical motion areas for 1500 GMT, July 25.

In harmony with these surface developments the 500-mb. level (fig. 6E) indicated a continued zonal flow over the central and northern portions of the eastern United States while the upper trough that had been somewhat persistent over the western portion of this area was being displaced eastward ahead of the new front.

As the closing phase of this situation on July 26 (fig. 7A, B), frontal decay removed the old discontinuity from the Eastern States and weakening occurred along the remaining portion of the front south of the 40th parallel in the eastern coastal waters. The new front continued its rapid eastward advance in the Great Lakes area. Approximately midway between these fronts was a rather well-defined trough apparent at the surface as well as aloft. It appeared that this surface trough was the reflection of the old upper trough that had been displaced rapidly eastward during the past 24 hours. Numerous showers and thunderstorms attended the passage of this trough while to its rear there was a general decrease in moisture and cloudiness, and a shift of the gradient winds to a more westerly direction. Thus a prolonged period of cool, damp weather from a spring-like frontal wave pattern was brought to a close.

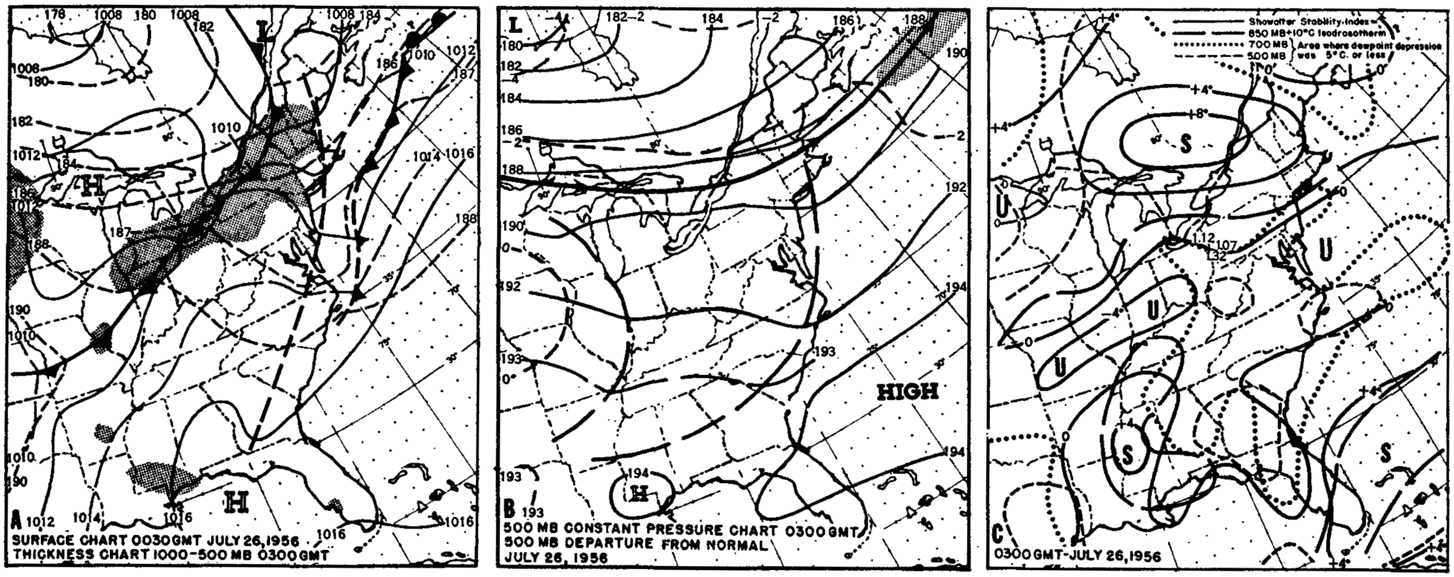

FIGURE 7.—(A) Sea level chart for 0030 GMT, and 1000–500-mb. thickness pattern (dashed) for 0300 GMT, July 26, 1956. Shading shows 24-hour precipitation areas ending at 0630 GMT, July 26. (B) 500-mb. contours and departure from normal, 200-mb. jet stream, and areas of winds of 75 knots or stronger; all for 0300 GMT, July 26, 1956. (C) Composite chart showing six semi-related items. 850-mb. dew point areas of +10° C. or higher, 700-mb. and 500-mb. areas with dew point depression 5° C. or less, calendar-day rainfall totals of 0.75 inch or more, and Showalter stability index values; all for 0300 GMT, July 26, 1956. Areas of positive vertical motion in excess of 0.005 m. p. s. (shaded) are for 1500 GMT, July 26.

4. PERSISTENCY OF THE COLD LOW

The retention of a frontal system for a prolonged period during the month of July over the extreme southern portion of the United States could only occur under ideal conditions. That such conditions were present during the period July 18–25 was best illustrated by the 700-mb. mean charts prepared by the Extended Forecast Section. These charts, though not shown, will be briefly reviewed. For a generalized presentation of the weather during the month of July with mean 700-mb. charts the reader may refer to the article in this issue by Krueger [15].

The 700-mb. departure from normal chart for the Northern Hemisphere for the 5-day period July 14–18 inclusive, depicts an area of strong positive anomalies encompassing the northern latitudes except for an intense negative anomaly of considerable size located between the North Pole and Alaska. From this hemispherical ring of positive anomalies, an arm-like area stretched southward along the western coast of North America reaching inland over the Southwestern States. Concurrently a large negative anomaly area existed over the New England States.

By the period of July 17–21 inclusive, the 700-mb. 5-day departure from normal chart presented the positive anomaly area over primarily the same region, although some intensification had occurred along the west coast of North America with a 320-ft. positive anomaly area over the northern portion of Vancouver Island and a plus 380-ft. anomaly center over northwestern Hudson Bay. The negative area over the New England region had split and weakened, indicating the probability of a building ridge in the New England area. A minus 130-ft. anomaly was located over Iowa.

For the 5-day period July 19–23, the 700-mb. departure from normal chart presented a crescent-shaped positive anomaly area over the North American Continent. This crescent-shaped anomaly extended from southern California northward into southwestern Canada, thence eastward across Hudson Bay, and finally recurved southeastward to southward until it reached the northern coast of Georgia. This positive anomaly area attained a value of 460 ft. over the central portion of Hudson Bay. In this position it completely blocked any movement of the negative departure from normal area that had a central value of minus 110 ft. over eastern Iowa.

This blocking condition was maintained in much the same pattern on the next 5-day 700-mb. departure from normal chart, except there had been a slight northeastward drift of the center of positive anomaly previously over the central portion of Hudson Bay thus allowing the below normal center with central value of minus 120 ft. to drift eastward into the southern portion of Lake Michigan.

5. TEMPERATURE DISTRIBUTION

The arrangement of the cyclonic and anticyclonic pressure areas over the central and eastern portions of Canada presented an ideal synoptic model for a wide-scale flow of cool air to stream southward from the Hudson Bay region into the northeastern sector of the United States. Since the Hudson Bay region is one of the main source areas for cool air during the summer months on the North American Continent, and since the northeastern section of the United States was experiencing a period of cool weather, we have an ideal situation for the advent and occurrence of much below normal temperatures. The outstanding temperature features of this study were not of record-breaking low readings at any one station or any group of stations, but rather the duration of these relatively pronounced departures from normal temperatures over a large area, i.e., most of northeastern United States. As shown by figure 1, the average daily temperatures were below normal every day from July 18–25 inclusive from the Ohio Valley to east-central Pennsylvania. In fact, the entire area north of the front was below normal at least 75 percent of the time. The area to the lee of the lower Great Lakes had the lowest frequency of below normal average temperatures in the Northeastern States as one would expect, nevertheless this area was below normal throughout most of the period.

In the *Weekly Weather and Crop Bulletin* [6], the chart depicting the departure of average temperatures from normal for the period July 16–22 inclusive (not shown) illustrates that all of the eastern half of the United States was below normal with the exception of the Southern Coastal States from Texas to North Carolina inclusive. The greatest temperature departures occurred from the Northern Plains through the New England area with anomalies of −6° F. or more, and locally in the upper Great Lakes region the departures were in excess of −9° F. during that 7-day period.

Further investigation has shown that on one or more days during the period of July 18–25, the maximum temperature receded to values of 10° F. or more below the monthly normal in the States north of the 37th parallel (fig. 1). This figure also indicates that at some time during the period nearly all of the eastern half of the nation recorded afternoon high temperatures 5° F. or more below normal monthly values, and that a small area in Michigan reported a departure of −20° F. with an almost equal value reported later in southwestern Missouri. It was apparent these low maximum temperatures were the principal contributing factor to the below normal average temperature that prevailed in the eastern half of the country. For, in contrast to the magnitude of the departure from normal of the maximum temperatures, the minimum readings were more on the order of 6° to 13° F. below the monthly minimum value over the Northeastern States, and were 3° to 7° F. under the normal values over the Southeastern States.

If one were to draw isochrones for the date of lowest maximum temperature during the period of July 18–25, this chart (not shown) would illustrate that the cold air had invaded only the northern portions of Illinois, Indiana, Ohio, and the extreme western portions of New York and Pennsylvania on July 18. But in the following three days this cooling engulfed most of the Northeastern States and a goodly portion of the South. However, over many of the Southern States the coldest daily maximum temperature did not occur until July 23–24.

The comparatively shallow cold air that prevailed over the Northeastern States due to the existent wind flow pattern could not possibly have been responsible for this late southern cooling, thus another source region must be located. Close examination of the 500-mb. temperatures as early as July 20 shows there was a marked thermal trough from western Kansas to the Texas Panhandle. As this cold thermal trough moved into the central and lower Mississippi Valley the 5- and 6-km. temperatures equaled and in some cases exceeded the minimum July temperature extremes previously recorded in the upper air [3]. It was this area of cold air that produced the rapid development of positive vertical motion near Springfield, Mo., on July 22. This comparatively deep mass of cold air served as the second source area for below normal surface temperatures. Concurrently with this happening the low-level flow over the Northern States east of the Appalachian Mountains had reversed and had become a more easterly or southeasterly flow. The source region for this flow was the airmass then over the region from Hudson Bay to Nova Scotia. This east-to-southeast flow of air was sufficiently cool to continue the below normal temperatures throughout the Northeastern States.

In conjunction with our discussion of below normal surface temperatures for this period it would be well to make reference to the departure from normal of the 1000–500-mb. thickness charts (not shown). In general, over the eastern portion of North America these charts, while similar in their general appearance to the 500-mb. departure from normal chart (figs. 3 to 7, B and E), were not quite as encompassing in area or intensity of negative values. Generally the extreme negative departures from the normal thickness values for July were under 400 ft. below the norm. For general comparison it might be stated that the 1000–500-mb. thickness pattern during this time was in rather good agreement with the 1000–500-mb. normal thickness for the month of September.

6. MOISTURE IN THE UPPER AIR

As previously mentioned there was no wide-scale transport of moisture directly northward from the Gulf of Mexico, July 18–25. The moisture that did invade the United States appeared to have traveled a rather circuitous route, either from the eastern Pacific Ocean or northward from the Gulf of Mexico over eastern Texas. However, in the latter days of this period the transport of moisture from the southern waters became somewhat more direct under a weak anticyclonic flow.

For the location of moisture areas at 0300 GMT, July 18, and at 24-hour synoptic periods thereafter, at the constant pressure levels of 850, 700, and 500 mb., a series of charts were prepared (figs. 3 to 7, C and F). On these charts has been reproduced by long-dashed lines the area within which at 850 mb. all dew points were 10° C. or higher.

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By means of dotted lines regions of moisture at 700 mb. have been depicted; within these enclosed areas the dew point departure from the observed temperature was 5° C. or less. The short-dashed lines represent the moisture areas at 500 mb. using the same definition as was applicable to the 700-mb. level. The numerical values of two or more digits scattered over the diagram represent calendar-day rainfall totals of 0.75 inch or more which occurred at a nearby first-order station.

With the inclusion of these moisture areas on the charts and accounting for normal advection for each 24 hours with attendant growth or shrinkage of these regions of moisture, it was observed by comparison (figs. 3 to 7, C and F) that practically all of any previous 24-hour rainfall pattern was enclosed by two or more of the moisture areas. Furthermore, it was clearly indicated that wherever heavy precipitation occurred these three levels of moisture were, for all practical purposes, superimposed over that area. In addition, it was interesting to note that the lack of moisture at the 700- and 500-mb. levels rather clearly differentiated the areas of no rainfall even though the 850-mb. dew point values were greater than 10° C.

Finally it was decided to include a fourth index upon these moisture charts and so, by use of continuous lines, the positive and negative areas of stability, as derived by Showalter [7], have been indicated.

7. INSTABILITY

With the interaction of the cold Low and its attendant low temperatures in the cP airmass to the north of the front, in direct contrast to the warm moist mT airmass south of the front, there is little doubt as to the probable occurrence of considerable instability. This instability was further indicated during the period by the development of showers and thunderstorms, as well as a few tornadoes. The Showalter Stability Index Charts [7] as prepared by the National Weather Analysis Center and presented in figures 3 to 7, C and F, show more quantitatively the distribution of the areas of convective stability and instability. These areas are outlined by the solid continuous lines with the positive areas marked by a plus sign and the negative area by a minus sign. Even a cursory examination of these charts clearly indicates the large negative or unstable zones near the fronts and in the areas associated with large rainfall totals. It must be remembered that the area of instability on these charts is for the time 0300 GMT and normal movement along the wind-flow pattern must be expected during the next 24-hour period in accounting for precipitation patterns that might be indicated as outside of its present area.

8. VERTICAL MOTION

For the areas where vertical motion prevailed during this period we shall rely on the charts that were prepared by the Joint Numerical Weather Prediction Unit (JNWP). The thermotropic model, utilizing the 1000-mb. and 500-mb. levels and dry adiabatic processes, yields an average vertical velocity which can be assumed to be centered near the 750-mb. level. Furthermore, while these velocities are representative of the average velocity over the area between grid points, it does not mean that smaller areas of increased or decreased vertical velocities could not occur within these smoothed contours. However, it was thought that it would be of interest to compare the location and intensity of the areas of positive vertical velocities, as produced by machine, with regions where precipitation occurred. It must be remembered that these vertical motion charts are prepared at 1500 GMT only and are 12 hours out of phase with all other upper air data that are shown. The shaded area on figures 3 to 7, C and F was the region where positive vertical velocity of 0.005 m. p. s. or higher was computed by the machine. The printed figures scattered over these charts are rainfall totals of 0.75 inch or more that occurred during the calendar day at a first-order weather station. Or, comparison may be made with the 24-hour precipitation pattern as depicted by the shaded area (figs. 3 to 7, A and D).

In order not to complicate figures 3 to 7, C and F further, the central values within the area of positive vertical motion were omitted, but for those who may be interested in these values they are as follows: July 18, 0.01 m. p. s.; July 19, 0.015 m. p. s.; July 20, 0.017; July 21, 0.015; July 22, 0.012, plus a new development indicated by a positive area that was formed by strong barotropic effects near Springfield, Mo., with 0.016 m. p. s. at the center (the day previous the highest positive velocity within reasonable radius was a 0.002 m. p. s. value); July 23, 0.008 m. p. s. near Eastport, Maine, and 0.007 m. p. s. near Little Rock, Ark.; July 24, 0.016 m. p. s. southeast of Sable Island, while the area previously over Arkansas dissipated.

It is interesting to note that while this area of vertical motion encloses a goodly portion of the rainfall area, it again leaves, as have other factors discussed in this paper, the utopia of precipitation forecasting far removed.

For example, by the use of Showalter's formula [8] in the computation of rates of precipitation expectancy from vertical motion:

$$I=\frac{w_0\rho_0(x_0-x_1)}{7}$$

where I is precipitation in inches per hour; w_0 is the vertical velocity in meters per second at the bottom of the column, i. e., condensation level; ρ_0 is the density of the air in gm./m.^{3} at the condensation level, and (x_0-x_1) is the difference in mixing ratio in gm./gm. at the condensation level and at the top of cloud or top of lift.

This formula has been further reduced by Showalter [9], using an approximation method, and designed for ease and speed of computation rather than for rigid exactness during the rapid preparation of quantitative rainfall estimations. He developed the following approximations dependent upon the surface dew point values:

For a dew point of	*I equals*
75°F.	$2w$
50°	w
35°	$w/2$

I=inches of rainfall per hour
w=vertical motion in meters per second

In cases such as warm frontal rains or orographic rainfall where slope is known, w can quickly be figured for the lift since it is a product of the slope and the speed of the wind component normal to the slope.

Furthermore, this abbreviated formula furnishes an easy and rapid means of computing the approximate value of the vertical velocity when the amount of precipitation that has occurred in a given length of time is known. For example: At Baltimore, Md., on July 20 it was reported that 4.26 inches of rain occurred in 24 hours, of which 4.25 inches fell in the last 12 hours of the day, 3.24 inches were collected in a 4-hour period, and 1.35 inches in a 1-hour period. The surface dew point temperature was near 72°F. Using the approximation formula and a value of $1.9w$ for the dew point of 72° F., we find that the vertical velocities were approximately 0.20 m. p. s. for the 12-hour period, 0.50 m. p. s. during the 4-hour rainfall, and 0.70 m. p. s. during the 1-hour downpour.

9. JET STREAM ANALYSIS

In this study it is interesting to note that the occurrence of a low-level jet stream was missing for the rapid transport of moisture from the Gulf of Mexico into the areas of heavy precipitation. Thus it appears that the bands of moisture necessary for the production of heavy rains over the Southeastern States arrived in these areas by means of normal advection, consequently eliminating the rapid replacement of moisture into these storm areas as would have occurred under low-level jet stream conditions. This in all probability reduced the total amount of precipitation that otherwise might have been obtained.

Generally the low-level winds over the Eastern States that were located north of the front and beneath the 7,000-ft. level maintained a cyclonic flow and a speed of 10–20 knots throughout the greater portion of the period. South of the front and beneath the same height level winds were variable as to direction while speeds were usually from 7 to 15 knots but locally approached 12–25 knots over Texas. Thus it appears that we must turn our attention to the upper levels of the atmosphere for a jet stream that had any influence upon the occurrence of precipitation.

The 300-mb., 200-mb., and 150-mb. charts all indicated that a well-defined jet stream was present on July 18 (fig. 3B) and was in good correlation with the surface front as observed by Palmén and Newton [10]. At these levels the jet stream continued to be maintained and remained in good agreement with the surface frontal position throughout most of the period. During July 18–21 there was also an easterly jet stream about the southern portion of the Bermuda High. This easterly flow of air apparently contained but little moisture since radiosonde observations reported that "motor-boating" had occurred in the lower levels of this jet stream.

It may be noted from the area of precipitation shown by the shaded zone on each chart (figs. 3 to 7, A and D) and by the position of the 200-mb. jet stream as illustrated on the 500-mb. constant level chart (figs. 3 to 7, B and E) that a large area of rainfall occurred during the period from July 18–25 along and to the north of the jet stream, although an almost equal-sized zone was reported to the south of the jet. In fact on the 20th the heaviest period of precipitation over a moderately sized area occurred well to the south of the jet stream which is in contrast to the findings of Starrett [11] and also of Riehl [12] who have stated that the concentration of precipitation both in frequency and amount usually occurs in or slightly to the north of the jet stream. However, it does appear in this case that the relation between frequency of rainfall and the location of the jet stream might have had a much closer agreement (see jet stream positions, figures 3 to 7, B and E and figure 2).

The southward displacement of the westerlies during this period is illustrated in figure 2, where the average position of the 700-mb. jet stream for July 1956 is shown to be about 300 miles south of the normal position for July jet streams. The actual average position of the jet stream for July 1956 is in relatively close agreement over the eastern half of the Nation with the normal positions of the jets for the month of May or November.

10. TROPOPAUSE RELATIONSHIP

In conjunction with the investigation of the high-level isotach charts the tropopause chart was studied in regard to possible breaklines in the regions of the strong jet streams at the 300-, 200-, and 150-mb. levels. It was thought that there might be some correlation between the area of heavy precipitation over the region from the Carolinas to southeastern Pennsylvania on the 19th and 20th. This was occasioned by the recent study by Culkowski [13] who mentioned that the southern or eastern edges of a tropopause breakline were the optimum locations for heavy precipitation. However, he cautioned that during the summer months the tropopause break area diminished in value as an indicator of excessive precipitation. In this case it appears there was no apparent correlation between the tropopause and the surface precipitation.

11. REGION OF HEAVIEST PRECIPITATION

It so happened during this period, July 18–25, that the area of maximum precipitation and the zone of greatest intensity of short-duration rainfall were in excellent conformity with each other. In reality this zone of excessive precipitation was a narrow band approximately 60 miles in width at its broadest part, which happened to be near Washington, D. C., and then tapered to blunted points near its northern and southern limits in the vicinities of Philadelphia, Pa., and a short distance south of Florence, S. C.

A combination of sundry factors conduced this unusual and heavy deposit of rain; in summation these contributing elements included:

1. An active front over the Southern States with stable waves traveling along this front.
2. A cold Low centered near Chicago, Ill., transporting southward some of the coolest air reported for July at 500 mb. and producing recurring impulses of cold air that aided in the genesis of waves.
3. An area of pronounced cyclonic vorticity at the 500-mb. level in phase with a developing and moving surface wave which progressed northeastward toward Washington, D. C., and which had begun acquiring unstable characteristics.
4. An intensification of a high pressure block both at the surface and aloft directly ahead of the developing wave.
5. A rapid sharpening of the upper trough attending the developing wave as it approached the building ridge that was holding over New England and along the eastern seaboard.
6. Creation of an area of pronounced cyclonic curvature and convergence by the intensification of the trough, a normally necessary feature according to Oliver and Oliver [14].
7. Advection into this region of 13° to 14° C. dew points at the 850-mb. level.
8. Advection of near saturated air over the region at the 700-mb. and 500-mb. levels.
9. A zone of positive vertical motion moving across the northern portion of this area.

Thus it would appear that conditions were nearly ideal for the occurrence of excessive rainfall.

Another condition or indication that appeared favorable for the occurrence of heavier rainfall along this narrow strip was the developing area of maximum anticyclonic vorticity displayed by the 1000–500-mb. thickness pattern just to the west of the region at 0300 GMT on the 20th; such an area is considered to be a region of maximum rainfall occurrence (see [12]). During the next 24 hours the thickness pattern developed an area of exceedingly strong anticyclonic vorticity and for the next 24 hours this zone continued to be advected across the southern portion of the New England States but with a considerable decrease in the negative relative vorticity.

12. PARTIAL EFFECTS FROM STORMS

During July 18–25, thunderstorms were frequent over a widespread area of the East; lightning killed several persons and damaged some property. Tornadoes were reported at Lorain, Ohio, Little Muskego Lake, Wis., Pennock, Minn., Falmouth, Ky., and Richmond, Va. Several severe windstorms were recorded. Hail in some local areas did considerable damage to crops and produce; Falmouth, Ky., reported 3 to 4 inches of hail on the ground on July 19. Cool, damp weather hindered agricultural interests by retarding crops and delaying the harvest in many areas.

However, heavy rains and the attendant local flooding of numerous streams accounted for the greatest number of lives lost and the largest property damage. Two lives were lost in the rain-swollen and rampant streams near Jackson Springs, N. C., on the 19th after a downpour of 9.15 inches. In Montgomery County, Md., the northern suburban section of Washington, D. C., 7 persons were drowned, 6 in cars driven into or swept into the swollen flash-flooded streams; the seventh was an attempted rescuer. It has been estimated by the River Services Section[1] that in a small core area approximately 20 miles north-northwest of Washington, D. C. at least 9 inches of rain occurred during a period of less than 12 hours and the greater portion of this total probably fell in less than 4 hours. This region is in the headwaters of Rock Creek basin, a moderate-sized creek which flows through the northern half of the District of Columbia. Damage in the Rock Creek basin was quite heavy. Flooding of streams occurred also at numerous places in eastern Maryland. Estimated damages to roads and bridges in southern Maryland totaled $300,000, with no report received from the northern section.

The Farm Bureau furnished a preliminary estimate of damages to farms, livestock, and feed of from $500,000 to $600,000. Thus, for a storm of short duration and of little moisture value, the cost was high.

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[1] The information received from River Services Section is tentative and may be subject to slight modification.

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